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QUARKONIA & PENTAQUARKS

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A brief review of the latest developments in the spectroscopy of heavy quarks is presented.
 The current status of the recently ‘discovered’ pentaquarks is also discussed.

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I am good at counting one, two. Three is difficult for me. So, I generally talk about mesons, and stay away from baryons. When the organizers asked me to talk also about pentaquarks, that became a real challenge. Since Frank Wilczek has told you all about the theoretical ideas behind pentaquarks, my job has become easier. I just have to tell you about experimental facts.

1. Heavy Quarkonia

Light quark ($n \equiv u, d, s$) spectroscopy is very rich, and very tough. The quarks are highly relativistic in the hadrons they make, the strong coupling constant α_s is very large (~ 0.6), and the u, d, s quarks have such similar masses that nearly all $|n\bar{n}\rangle$ mesons are mixtures of all three flavours. This results in a very high density of overlapping states, difficult to disintangle, and even more difficult to understand. In contrast, the charm (c) and beauty (b) quarks are heavy enough so that relativistic problems are not too serious ($\langle v^2/c^2 \rangle \approx 0.1 - 0.2$), α_s is not too large, ($\alpha_s \approx 0.2 - 0.3$), and charmonium $|c\bar{c}\rangle$ and bottomonium $|b\bar{b}\rangle$ states are few and well resolved (see Fig. 1). This makes the spectroscopy of $|c\bar{c}\rangle$ and $|b\bar{b}\rangle$ particularly useful for the study of Quantum Chromodynamics.

1.1. Charmonium

This is where all of it began with the 1974 discovery of J/ψ . From 1974–1985 a lot of discovery physics in charmonium was done at SLAC, ORSAY and DESY, but precision was often lacking, except for the vector states which could be directly produced in e^+e^- annihilation. Width of triplet P-wave states could not be determined, and except for the ground state, no singlet S- and P-wave states could be successfully identified. The region above the $D\bar{D}$ threshold essentially remained.

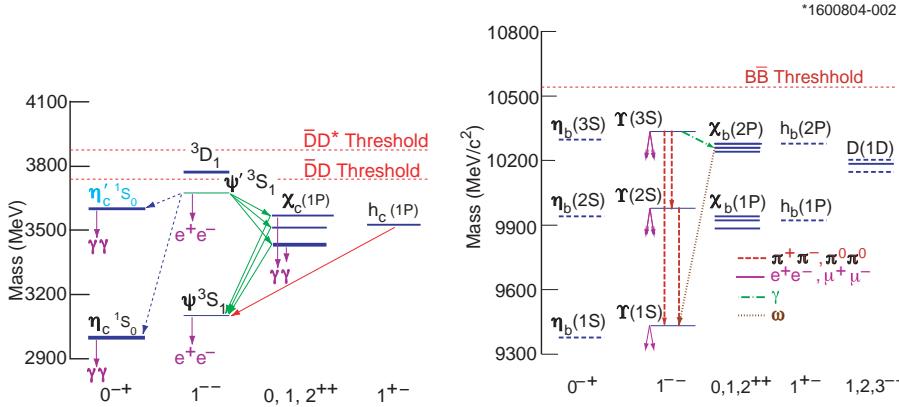


Fig. 1. Spectra of quarkonium states, (left) charmonium, (right) bottomonium.

During 1990–2000, the Fermilab experiments E760 and E835 exploited the ability of $p\bar{p}$ annihilations to make precision measurements of the masses and widths of 3S_1 (J/ψ , ψ'), and 1P_1 (χ_0 , χ_1 , χ_2) states, but were not so successful in making equally precise measurements of the singlet state 1S_0 (η_c), and failed in identifying 2S_0 (η'_c) and 1P_1 (h_c). The region above $D\bar{D}$ threshold remained *terra incognita*. For a review see Ref. 1.

During the 1990s, the BES detector at the Beijing Electron-Positron Collider (BEPC) made important contributions in charmonium spectroscopy, primarily by investing much greater luminosity ($\sim \times 10$) than SLAC+ORsay+DESY. They also made some important excursions in the region above the $D\bar{D}$ threshold.

More recently, new players have emerged in the field. The CLEO detector at the CESR accelerator at Cornell, the Belle detector at KEK, and the BaBar detector at PEP II at Stanford, are all beginning to produce extremely interesting results. I am going to describe some of these below. In somewhat more distant future (2008 –) we expect new accelerators, BEPC II and FAIR at GSI, to come online and provide further insight into the physics of this mass region.

1.1.1. The Spin Singlet States and the Hyperfine Interaction

The spin-independent $q\bar{q}$ interaction is well understood in terms of one-gluon exchange, and is very successfully modeled by a Coulombic $1/r$ potential. The spin dependence which follows from this is also accepted. What is not understood is the nature of the confinement part of the interaction, which is generally modeled by a scalar potential proportional to r . A crucial test of the Lorenz nature of the confinement potential is provided by the measurement of hyperfine or spin-singlet/spin-triplet splittings. A scalar potential does not contribute to the spin-spin or hyperfine interaction, whereas for a Coulombic potential it is a contact interac-

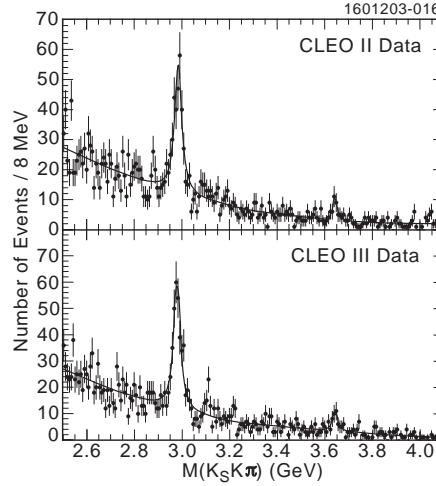


Fig. 2. CLEO discovery of $\eta'_c(2^1S_0)$ in two photon formation, and decay into $K_SK^\pm\pi^\mp$.

tion. As a consequence hyperfine splitting is predicted to be finite only for S-wave states, and to be zero for P-wave and higher L-states

1.1.2. Hyperfine Splitting in S-wave Quarkonia

No singlet states have so far been identified in bottomonium. In charmonium, however, it has been established for a long time that $\Delta M(1S)_{hf} \equiv M(J/\psi, 1^3S_1) - M(\eta_c, 1^1S_0) = 172 \pm 2$ MeV. It is interesting to determine the size of the hyperfine splitting of $2S$ states, which sample the confinement region more deeply. Long ago Crystal Ball² claimed the identification of η'_c with $M(\eta'_c) = 3594 \pm 5$ MeV, leading to $\Delta M(2S)_{hf} = 92 \pm 5$ MeV, which kind of made sense with $\Delta M(1S)_{hf} = 172 \pm 2$ MeV. Most potential model calculations tried to accomodate this ‘experimental’ result, although it was not confirmed by any subsequent measurement, and was actually dropped by the PDG meson summary.

The search for η'_c has finally ended. Belle³ announced it first in two different decays of large samples of B-mesons. CLEO⁴ and BaBar⁵ both have identified it in the two-photon fusion reaction, $e^+e^- \rightarrow (e^+e^-)\gamma\gamma, \gamma\gamma \rightarrow \eta'_c \rightarrow K_SK\pi$. The CLEO measurement is shown in Fig. 2. The exciting part of these measurements is that $M(\eta'_c)_{avg} = 3637.4 \pm 4.4$ MeV, which is almost 50 MeV larger than the old Crystal Ball claim, and it leads to a surprisingly small hyperfine splitting, $\Delta M(2S)_{hf} = 48.6 \pm 4.4$. It is too early to say whether this can be explained in terms of channel mixing⁶, or unexpected contribution from the confinement potential.

1.1.3. Hyperfine Splitting in *P*-wave Quarkonia

As mentioned already, hyperfine splitting is expected to be zero in all except S-wave states if the confinement potential is scalar, as is generally assumed. Thus it is expected that $\Delta M(1P)_{hf} \equiv \langle M(1^3P_J) \rangle - M(1^1P_1) = 0$, except for higher order contributions of no more than an MeV or two. Unfortunately, while $\langle M(1^3P_J) \rangle = 3525.31 \pm 0.07^7$, the $h_c(1^1P_1)$ has not been firmly identified. Let me however, give you a preview with the statement that both Fermilab E835 and CLEO are working on the search for h_c . The E835 experiment is analyzing the reactions $p\bar{p} \rightarrow h_c \rightarrow \pi^0 J/\psi$ and $p\bar{p} \rightarrow h_c \rightarrow \gamma\eta_c$, and preliminary results are that while the first reaction does not have a signal for h_c formation⁸, the second may have. The CLEO team is analyzing $e^+e^- \rightarrow \psi' \rightarrow \pi^0 h_c, h_c \rightarrow \gamma\eta_c$ but has not presented any results so far [Note: Since the conference, CLEO has announced its preliminary results with $M(h_c) = 3524.8 \pm 0.7$ MeV⁹ with the consequent $\Delta M(1P)_{hf} = 0.6 \pm 0.6$ MeV. It appears that there is no significant departure from the simple expectation, $\Delta M(1P)_{hf}=0$].

1.1.4. The $\rho - \pi$ Problem

Since the widths for leptonic decays, as well as 3 gluon decays to light hadrons, of both J/ψ and ψ' depend on the wave functions at the origin, pQCD predicts the equality of the ratios of branching ratios

$$\frac{B(\psi' \rightarrow l^+l^-)}{B(J/\psi \rightarrow l^+l^-)} = (13 \pm 2)\% = \frac{B(\psi' \rightarrow LH)}{B(J/\psi \rightarrow LH)}.$$

This expectation has been extended to ratios of individual hadronic decays, and has led to many measurements by BES and CLEO to test it. The results is that while the sums of all hadronic decays do seem to follow this expectation, and $\sum_i B(\psi' \rightarrow LH)_i / \sum_i B(J/\psi \rightarrow LH)_i = (17 \pm 3)\%$, individual decays show large departures from it, the ratio being as small as 0.2% for $\rho\pi$ decays. While many exotic theoretical suggestions have been made to explain these deviations, it appears that what we are witnessing is the failure of attempts to stretch pQCD beyond its limits of validity.

1.1.5. Higher Vector States

For a long time the parameters listed in the PDG compilation for the three vector states above the $D\bar{D}$ threshhold have been based on the R-parameter measurement by the DASP group¹⁰, even though none of the other measurements of R agreed with it. Recent measurements by the BES group¹¹ have finally allowed us¹² to make a reliable determination of these parameters. The result is that the total and leptonic widths of these states have changed by large amounts, e.g. $\Gamma(4039) = 88 \pm 5$ MeV, instead of 52 ± 10 MeV. Similar other new results are $\Gamma(4153) = 107 \pm 8$ MeV, $\Gamma(4426) = 119 \pm 15$ MeV.

1.2. Bottomonium

Despite the fact that the bottomonium $b\bar{b}$ system is certainly more amenable to pQCD, we know far less about bottomonium than we know about charmonium. The η_b , ground state of bottomonium, has not been identified so far. The vector states $\Upsilon(1S, 2S, 3S)$ and $4S$) are known but only one hadronic transition from these, $\Upsilon(nS) \rightarrow \Upsilon(n'S)\pi^+\pi^-$ ($n' < n$) has ever been observed. Radiative transitions $\Upsilon(nS) \rightarrow \gamma\chi_b(n'^3P)$ states have been observed. No D-states, which are expected to be bound (see Fig. 1) have been observed. No hadronic transition from any χ_b states has ever been observed. Recently, CLEO had made small gains in both the above problems. The 1^3D_2 state has been successfully observed in 4-photon cascade $\Upsilon(3S) \rightarrow \gamma_1(2P) \rightarrow \gamma_1\gamma_2(1D) \rightarrow \gamma_1\gamma_2\gamma_3(1P) \rightarrow \gamma_1\gamma_2\gamma_3\gamma_4\Upsilon(1S)$, $\Upsilon(1S) \rightarrow l^+l^-$. The mass $M(1^3D_2) = 10,161.1 \pm 0.6 \pm 1.6$ MeV¹³. In another measurement, $\Upsilon(3S) \rightarrow \gamma\chi_b(2P), \chi_b(1, 2) \rightarrow \omega\Upsilon(1S)$ has also been observed¹⁴.

2. Exotics

I was going to talk about the classical exotics of QCD, the glueballs and hybrids, but because of the request of the conference organizers to talk about pentaquarks, I will simply refer you to my last review of glueballs and hybrids¹⁵. To summarize, no consensus candidates for scalar or tensor glueballs have emerged so far. Candidates for $|q\bar{q}g\rangle$ hybrids with exotic $J^{PC} = 1^{-+}$ have indeed been claimed amid plenty of controversy.

Having been released from glueballs and hybrids, I can indulge in another class of exotics. These are the unexpected, uninvited, and therefore the exotic hadrons which have recently shown up in several hadron spectroscopy experiments.

The first of these was the discovery of narrow ($\Gamma < 7$ MeV) D_{sJ} resonances with $M(D_s^{*+}, J^P = 0^+) = 2317$ MeV, and $M(D_s^{*+}, J^P = 1^+) = 2462$ MeV by BaBar¹⁶ and CLEO¹⁷. These states were expected at higher masses and therefore with large widths. Instead, they show up temptingly just below DK and D^*K thresholds, giving encouragement to molecular enthusiasts.

The second exotic is the discovery by Belle¹⁸ of a narrow resonance in B decays, which was quickly confirmed by CDF. This resonance, dubbed $X(3872)$, has a mass of 3872 ± 1 MeV, a width < 2.5 MeV, and decays (it appears almost exclusively) to $\pi^+\pi^-J/\psi$. Again, since its mass, width, and decay make it difficult to fit it into the charmonium spectrum, and since $M(D^0) + M(\bar{D}^{*0}) = 3872$ MeV, it has provided more fodder to $|D^0\bar{D}^{*0}\rangle$ molecule enthusiasts. At CLEO we have searched for this state in untagged two photon fusion (therefore $J^{PC} = 0^{\pm,+}, 2^{\pm,+}, \dots$) and in ISR (initial state radiation) mediated production, and have established quite stringent upper limits on its population in either production mode¹⁹.

I finally come to the hotter than hot topic of...

3. Pentaquarks

The pentaquark story starts with the announcement by LEPS at Osaka²⁰ that there was a significant enhancement in the missing mass spectrum for γK^- in the reaction $\gamma n \rightarrow K^+ K^- n$ with photons incident on a plastic scintillator (CH) target. The missing mass spectrum was interpreted to indicate a $|K^+ n >$ state dubbed Θ^+ , with mass $M(\Theta^+) = 1.54 \pm 0.01$ GeV, and width $\Gamma(\Theta^+) < 25$ MeV, with statistical significance of 4.6σ . If true, the state had strangeness $S = +1$, and had to have at least five quarks. The pentaquark was born! In quick succession, CLAS claimed confirmation in photons incident on deuterium²¹, and hydrogen²², SAPHIR in $\gamma + p$ ²³, ZEUS²⁴ in $e^+ p$ and $e^- p$ inelastic scattering, HERMES²⁵ in $e^+ d$ inelastic scattering, YEREVAN in $p +$ propane²⁶, DIANA²⁷ in $K^+ +$ Xenon, SVD in $p +$ Si²⁸, and COSY in $p + p$ ²⁹. Neutrinos were also not left behind, and ITEP³⁰ claimed Θ^+ in $\nu + H_2, D_2, Ne$ data from CERN and FNAL. In my memory, never before has such a stampede been witnessed!

The theoretical model for Θ^+ which was in vogue is the antidecuplet model of Jaffe and Wilczek³¹. According to this model, there should be ($S = 0$) N^* , ($S = -1$) Σ , and ($S = -2$) Ξ cascade pentaquarks also. Sure enough, NA49³² announced the observation of $\Xi(1862)$ as the $S = -2$ pentaquark in the reaction $p + p \rightarrow X + (\Xi^-\pi^-)$. Going one step further, H1³³ claimed the observation of a charmed pentaquark $\Theta_c(3099)$ in the reaction $e + p \rightarrow (D^* p)$.

One would think that with so many positive observations there is no doubt that pentaquarks exist. Unfortunately, this is not so. There are two reasons. The first is illustrated in my Table I. The fact is that despite the claimed significance levels up to 7.8σ , a conservative uniform determination of significance, $\sigma = S/\sqrt{S + 2B}$, where S and B are signal and background counts respectively, leads to the fact that none of the significance levels rises to the level of 5σ , the criterion used by Physical Review Letters for a claim of observation.

The second reason is much more important. Since pentaquarks are so novel and exciting, many more experiments have attempted to find them, but failed. Those which have tried, but failed to find Θ^+ include BES³⁴, FNAL E690³⁵, FNAL E871 (HyperCP)³⁶, CDF³⁷, BaBar³⁸, ALEPH³⁹, DELPHI⁴⁰, PHENIX ($\bar{\Theta}$)⁴¹, and HERA-B⁴². Similarly, CDF³⁷, BaBar³⁸, ALEPH³⁹, HERA-B⁴², and ZEUS⁴³ find no evidence for $\Xi(1860)$. CDF³⁷, ALEPH³⁹, ZEUS²⁴, and FNAL E831 FOCUS⁴⁴ also find no evidence for Θ_c . It is not looking very good for the survival of any of the pentaquarks!

Finally, I have to confess to my personal skepticism about pentaquarks. Nearly two decades ago, there was a similar stampede for the existence of dibaryons, and for several years I made valiant searches for them. While claims for nearly 40 dibaryons with masses between 1900 and 2250 MeV were made, not a single one survived high resolution, high statistics measurements⁴⁵.

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Note: The references listed below include several which were not published at

Mass (MeV)	Width (MeV)	N	Signif. Claimed	Uniform signif.	Reaction $A + B \rightarrow X + \Theta$	Experiment
$\Theta^+(1540)$						
$1540 \pm 10 \pm 5$	< 25	19	4.6σ	$\sim 2.7\sigma$	$\gamma + C \rightarrow X + (nK^+)$	LEPS
$1542 \pm 2 \pm 5$	< 21	43	5.2σ	$\sim 3.5\sigma$	$\gamma + d \rightarrow X + (nK^+)$	CLAS
$1540 \pm 4 \pm 3$	< 25	63	4.8σ	$\sim 4.3\sigma$	$\gamma + p \rightarrow X + (nK^+)$	SAPHIR
$1555 \pm 1 \pm 10$	< 26	41	7.8σ	$\sim 4.0\sigma$	$\gamma + p \rightarrow X + (nK^+)$	CLAS
$1539 \pm 2 \pm 2$	< 9	29	4.4σ	$\sim 3.0\sigma$	$K^+ + Xe \rightarrow X + (pK_s^0)$	DIANA
$1533 \pm 5 \pm 3$	< 20	27	6.7σ	$\sim 4.0\sigma$	$\nu + Ne \rightarrow X + (pK_s^0)$	ITEP
1528 ± 4	< 19	60	5.8σ	$\sim 4.0\sigma$	$\gamma^* + d \rightarrow X + (pK_s^0)$	HERMES
$1526 \pm 3 \pm 3$	< 24	50	5.6σ	$\sim 3.5\sigma$	$p + Si \rightarrow X + (pK_s^0)$	SVD-2
1530 ± 5	< 18	50	3.7σ	$\sim 3.7\sigma$	$p + p \rightarrow X + (pK_s^0)$	COSY
1545 ± 12	< 40	100	5.5σ	$\sim 4.0\sigma$	$p + p \text{ prop} \rightarrow X + (pK_s^0)$	YEREVAN
$1522 \pm 2 \pm 3$	< 6	221	4.6σ	$\sim 3.6\sigma$	$\gamma^* + p \rightarrow X + (p^\pm K_s)$	ZEUS
$\Xi(1862)$						
$(S = -2)$						
1862 ± 2	< 21	65	5.8σ	$\sim 4.7\sigma$	$p + p \rightarrow X + (\Xi^- \pi^-)$	NA49
$\Theta(3099)$						
$(C = -1)$						
$3099 \pm 3 \pm 5$	< 35	51	5.4σ	$\sim 4.2\sigma$	$e + p \rightarrow X + (D^* p)$	HERA

the time of the conference, but have become available since then.

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